# Bianchi Type-IX Cosmological Model with a Perfect Fluid in *f(R)* Theory of Gravity

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## ABSTRACT

Bianchi type-IX space-time is considered in the framework of the $f(R)$ theory of gravity when the source of the energy momentum tensor is a perfect fluid. The cosmological model is obtained by using the condition that the expansion scalar ($\theta$) is proportional to the shear scalar ($\sigma$). The physical and geometrical properties of the model are also discussed.

*Keywords:* $f(R)$ *gravity, Bianchi type-IX space-time*

## 1. INTRODUCTION

Cosmological observations in the late 1990's from different sources such as the Cosmic Microwave Background Radiation (CMBR) and supernova (SN Ia) surveys indicate that the universe consist of 4% ordinary matter, 20% dark matter (DM) and 76% dark energy (DE) [1-4]. The DE has large negative pressure while the pressure of DM is negligible. Wald [5] has distinguished DM and DE and clarified that ordinary matter and DM satisfy the strong energy conditions, whereas DE does not. The DE resembles with a cosmological constant and the self-interaction potential of scalar fields. The scalar field is provided by the dynamically changing DE including quintessence, k-essence, tachyon, phantom, ghost condensate and quintom etc. The study of high redshift supernova experiments [6-8], CMBR [9-10], large scale structure [11] and recent evidences from observational data [12-14] suggest that the universe is not only expanding but also accelerating.

There are two major approaches to the problem of accelerating expansion. One is to introduce a DE component in the universe and study its effects. The alternative is to modify general relativity; this is termed as modified gravity approach. We are interested in second approach. After the introduction of General Relativity (GR) in 1915, questions related to its limitations were in discussion. Einstein pointed out that Mach's principle is not substantiated by general relativity. Several attempts have been made to generalize the general theory of gravitation by incorporating Mach's principle and other desired features which were lacking in the original theory. Alternatives to Einstein's theory of gravitation have been proposed incorporating certain desirable features in the general theory. In recent decades, as an alternative to general relativity, scalar tensor theories and modified theories of gravitation have been proposed. The most popular amongst them include the theories of Brans-Dicke [15], Nordtvedt [16], Sen [17], Sen and Dunn [18], Wagonar [19], Saez-Ballester [20] etc. Recently, $f(R)$ gravity and $f(R,T)$ gravity theories have gained importance amongst the modified theories of gravity because these theories are supposed to provide natural gravitational alternatives to dark energy. Among the various modifications, the $f(R)$ theory of gravity is treated most suitable due to cosmologically important $f(R)$ models. In $f(R)$ gravity, the Lagrangian density $f$ is an arbitrary function of $R$ [15, 21-23]. The model with $f(R)$ gravity can lead to the accelerated expansion of the universe. A generalization of $f(R)$ modified theory of gravity was proposed by Takahashi and Soda [24] by including explicit coupling of an arbitrary function of the Ricci scalar $R$ with the matter Lagrangian density $L_m$. There are two formalisms to deriving field equations from the action in $f(R)$ gravity. The first is the standard metric formalism in which the field equations are derived by the variation of the action with respect to the metric tensor $g_{\mu\nu}$. The second is the Palatini formalism. Maeda [25] have investigated Palatini formulation of the non-minimal geometry-coupling models. Multamaki and Vilja [26] obtained spherically symmetric solutions of modified field equations in $f(R)$ theory of gravity. Akbar and Cai [27] studied $f(R)$ theory of gravity action as a nonlinear function of the curvature scalar $R$. Nojiri and Odinstove [28-30] derived the result that a unification of the early time inflation and late time acceleration is allowed in $f(R)$ theory. Ananda, Carloni and Dunsby [31] studied structure growth in $f(R)$ theory with a dust equation of state. Sharif and Shamir [32] and Sharif [33] have studied the vacuum solutions of Bianchi type-I, V and VI space-times. Sharif and Shamir [34] and Sharif and Kausar [35] obtained the non-vacuum solutions of Bianchi type-I, III and V space-times in $f(R)$ theory of gravity. Adhav [36, 37] have investigated the Kantowski-Sachs string cosmological model and the Bianchi type-III cosmological model with a perfect fluid in $f(R)$ gravity. Singh and Singh [38] have obtained functional form of $f(R)$ with power-law expansion in Bianchi type-I space-times. Recently Jawad and Chattopadhyay [39] have investigated new holographic dark energy in $f(R)$ Horava Lifshitz gravity. Rahman et al. [40] have obtained non-commutative wormholes in $f(R)$ gravity with Lorentzian distribution.

Motivated by the above investigations, in this paper an attempt is made to study Bianchi type-IX space-time when the universe is filled with a perfect fluid in the $f(R)$ theory of gravity with standard metric formalism. Bianchi type-IX space-time is of vital importance in describing cosmological models during the early stages of evolution of the universe. This work is organized as follows: In Section 2, the $f(R)$ gravity formalism is introduced. In Section 3, the model and field equations are presented. The field equations are solved in Section 4. The physical and geometrical behavior of the model is discussed in Section 5. Section 6 contains concluding remarks.

## 2. $f(R)$ GRAVITY FORMALISM:

The action of $f(R)$ gravity is given by

$$S = \int \sqrt{-g}\left(\frac{1}{16\pi G} f(R) + L_m\right) d^4x \,. \tag{1}$$

Here $f(R)$ is a general function of the Ricci scalar $R$ and $L_m$ is the matter Lagrangian. The corresponding field equations of $f(R)$ gravity are found by varying the action with respect to the metric $g_{\mu\nu}$:

$$F R_{\mu\nu} - \frac{1}{2} f(R) g_{\mu\nu} - \nabla_\mu \nabla_\nu F + g_{\mu\nu} \Box F = k T_{\mu\nu} \,, \tag{2}$$

where $F = \frac{d}{dR} f(R)$, $\Box \equiv \nabla^\mu \nabla_\nu$, $\nabla_\mu$ is the covariant derivative and $T_{\mu\nu}$ is the standard matter energy-momentum tensor derived from the Lagrangian $L_m$.

Taking the trace of the above equation (with $k = 1$), we obtain

$$F R - 2 f(R) + 3 \Box F = T \,. \tag{3}$$

On simplification, equation (3) leads to

$$f(R) = \frac{F R + 3\nabla^\mu \nabla_\mu F - T}{2} \,. \tag{4}$$

## 3. METRIC AND FIELD EQUATIONS:

Bianchi type-IX metric is considered in the form,

$$ds^2 = -dt^2 + a^2 dx^2 + b^2 dy^2 + \left(b^2 \sin^2 y + a^2 \cos^2 y\right) dz^2 - 2a^2 \cos y dx dz, \tag{5}$$

where $a, b$ are scale factors and are functions of cosmic time $t$.

The Ricci scalar for Bianchi type-IX model is given by

$$R = -2\left[\frac{\ddot{a}}{a} + 2\frac{\ddot{b}}{b} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{\dot{b}^2}{b^2} + \frac{1}{b^2} - \frac{a^2}{4b^4}\right]. \tag{6}$$

The energy momentum tensor for the perfect fluid is given by

$$T_{ij} = (\rho + p)u_i u_j - p g_{ij}, \tag{7}$$

satisfying the barotropic equation of state

$$p = \gamma \rho, \; 0 \le \gamma \le 1, \tag{8}$$

where $\rho$ is the energy density and $p$ is the pressure of the fluid.

In co-moving coordinates

$$T_1^1 = T_2^2 = T_3^3 = -p, \; T_4^4 = \rho, \;\; T = \rho - 3p. \tag{9}$$

With the help of equations (7) to (9), the field equations (2) for the metric (5) are found

$$\left(\frac{\ddot{a}}{a} + 2\frac{\ddot{b}}{b}\right)F + \frac{1}{2} f(R) + \left(\frac{\dot{a}}{a} + 2\frac{\dot{b}}{b}\right)\dot{F} = -\rho, \tag{10}$$

$$\left(\frac{\ddot{a}}{a} + 2\frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{a^2}{2b^4}\right)F + \frac{1}{2} f(R) + \ddot{F} + 2\frac{\dot{b}}{b}\dot{F} = p, \tag{11}$$

$$\left(\frac{\ddot{b}}{b} + \frac{\dot{b}^2}{b^2} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} + \frac{1}{b^2} - \frac{a^2}{2b^4}\right)F + \frac{1}{2} f(R) + \ddot{F} + \left(\frac{\dot{a}}{a} + \frac{\dot{b}}{b}\right)\dot{F} = p, \tag{12}$$

where the overdot $(\dot{\ })$ denotes the differentiation with respect to *t*.

## 4. SOLUTIONS OF FIELD EQUATIONS:

The field equations (10) to (12) are highly non-linear differential equations in five unknowns $a, b, p, \rho, F$. Hence to obtain a well determined solution of the system, we assume that the square of the expansion scalar ($\theta$) is proportional to the shear scalar ($\sigma^2$) [41], which leads to

$$a = b^m, \; (m \neq 1), \tag{13}$$

where $m$ is proportionality constant.

Also the power law relation between the scale factor $(A)$ and scalar field ($F$) [37, 42-43] has been given by

$$F \, \alpha \, A^{n} \ , \qquad (14)$$

where $n$ is an arbitrary constant and $A$ is the average scale factor.

For the metric (5), the average scale factor $A$ is

$$A = (ab^{2})^{\frac{1}{3}} . \qquad (15)$$

Equation (14) leads to

$$F = K \, A^{n} \ , \qquad (16)$$

where $K$ is a proportionality constant.

With the help of equations (13) and (15), equation (16) reduces to

$$F = K \, b^{\frac{(m+2)n}{3}} \ . \qquad (17)$$

Subtracting equation (10) from (11) and (12) respectively and dividing the result by $F$ gives

$$2\frac{\dot{a}}{a}\frac{\dot{b}}{b} - 2\frac{\ddot{b}}{b} + \frac{a^{2}}{2b^{4}} + \frac{\ddot{F}}{F} - \frac{\dot{a}}{a}\frac{\dot{F}}{F} = \frac{p+\rho}{F} , \qquad (18)$$

$$\frac{\dot{a}}{a}\frac{\dot{b}}{b} - \frac{\ddot{a}}{a} - \frac{\ddot{b}}{b} + \frac{\dot{b}^{2}}{b^{2}} + \frac{1}{b^{2}} - \frac{a^{2}}{2b^{4}} + \frac{\ddot{F}}{F} - \frac{\dot{b}}{b}\frac{\dot{F}}{F} = \frac{p+\rho}{F} . \qquad (19)$$

Subtracting equation (19) from equation (18) yields

$$\frac{\ddot{a}}{a} - \frac{\ddot{b}}{b} + \frac{\dot{a}}{a}\frac{\dot{b}}{b} - \frac{\dot{a}}{a}\frac{\dot{F}}{F} + \frac{\dot{b}}{b}\frac{\dot{F}}{F} - \frac{1}{b^{2}} - \frac{\dot{b}^{2}}{b^{2}} + \frac{a^{2}}{b^{4}} = 0 . \qquad (20)$$

With the help of equations (13) and (17), equation (20) leads to

$$\frac{\ddot{b}}{b} + \frac{(3m^{2} - m^{2}n - mn + 2n - 3)}{3(m-1)}\frac{\dot{b}^{2}}{b^{2}} - \frac{1}{(m-1)b^{2}} + \frac{b^{2m-4}}{(m-1)} = 0 . \qquad (21)$$

Multiplying equation (21) by $2b$

$$2\ddot{b} + \frac{2(3m^{2} - m^{2}n - mn + 2n - 3)}{3(m-1)b}\dot{b}^{2} = \frac{2}{(m-1)}\left[b^{-1} + b^{2m-3}\right] . \qquad (22)$$

Let

$$\frac{d}{db}(\dot{b}^{2}) = \frac{d}{dt}(\dot{b}^{2})\frac{dt}{db} = 2\ddot{b} . \qquad (23)$$

With the help of equation (23), equation (22) reduces to

$$\frac{d}{db}(\dot{b}^{2}) + \frac{2(3m^{2} - m^{2}n - mn + 2n - 3)}{3(m-1)b}(\dot{b}^{2}) = \frac{2}{(m-1)}\left(b^{-1} - b^{2m-3}\right) . \qquad (24)$$

This is linear differential equation of order one.

Integrating equation (24) with respect to $b$

$$\dot{b}^2 = \frac{3}{(3m^2 - m^2n - mn + 2n - 3)} - \frac{3}{(6m^2 - m^2n - mn - 6m + 2n)} b^{2(m-1)}. \tag{25}$$

Taking square root

$$\dot{b} = \sqrt{\frac{3}{(3m^2 - m^2n - mn + 2n - 3)} - \frac{3}{(6m^2 - m^2n - mn - 6m + 2n)} b^{2(m-1)}}. \tag{26}$$

Using equations (13) and (26), metric (5) reduces to

$$ds^2 = \left\{ \begin{array}{l} -\dfrac{1}{\left\{ \dfrac{3}{(3m^2 - m^2n - mn + 2n - 3)} - \dfrac{3}{(6m^2 - m^2n - mn - 6m + 2n)} b^{2(m-1)} \right\}} db^2 \\ + b^{2m} dx^2 + b^2 dy^2 + \left(b^2 \sin^2 y + b^{2m} \cos^2 y\right) dz^2 - 2b^{2m} \cos y\, dx dz \end{array} \right\}. \tag{27}$$

Using the new coordinate $b = T$ , equation (27) leads to

$$ds^2 = \left\{ \begin{array}{l} -\dfrac{1}{\left\{ \dfrac{3}{(3m^2 - m^2n - mn + 2n - 3)} - \dfrac{3}{(6m^2 - m^2n - mn - 6m + 2n)} b^{2(m-1)} \right\}} dT^2 \\ + T^{2m} dx^2 + T^2 dy^2 + \left(T^2 \sin^2 y + T^{2m} \cos^2 y\right) dz^2 - 2b^{2m} \cos y\, dx dz \end{array} \right\}. \tag{28}$$

## 5. SOME PHYSICAL PROPERTIES OF THE MODEL:

The physical quantities such as the spatial volume $V$ , Hubble parameter $H$ , expansion scalar $\theta$, mean anisotropy parameter $A_m$, shear scalar $\sigma^2$ , energy density $\rho$ are obtained as follows:

The spatial volume is in the form,

$$V = T^{m+2}. \tag{29}$$

The Hubble parameter is given by

$$H=\frac{(m+2)}{3T}\left(\frac{3}{(3m^2-m^2n-mn+2n-3)}-\frac{3}{(6m^2-m^2n-mn-6m+2n)}T^{2(m-1)}\right)^{1/2}. \quad (30)$$

The Expansion scalar is,

$$\theta=\frac{(m+2)}{T}\left(\frac{3}{(3m^2-m^2n-mn+2n-3)}-\frac{3}{(6m^2-m^2n-mn-6m+2n)}T^{2(m-1)}\right)^{1/2}. \quad (31)$$

The mean anisotropy parameter is,

$$A_m=\frac{2(m-1)^2}{(m+2)^2}=\text{constant } (\neq 0 \text{ for } m\neq 1). \quad (32)$$

The shear scalar is given by,

$$\sigma^2=\left\{\frac{(m-1)^2}{(3m^2-m^2n-mn+2n-3)}T^{-2}-\frac{(m-1)^2}{(6m^2-m^2n-mn-6m+2n)}T^{2(m-2)}\right\}. \quad (33)$$

We observe that,

$$\frac{\sigma^2}{\theta^2}=\frac{(m-1)^2}{3(m+2)^2}=\text{constant } (\neq 0)\text{, for } m\neq 1. \quad (34)$$

Using equations (8), (17) and (26) in equation (10), the energy density is obtained as

$$\rho=\frac{K}{2(1+\gamma)}T^{\frac{mn+2n-6}{3}}\left(\begin{array}{l}1+\dfrac{9(1+4m-m^2)+(mn+2n)(2mn-3m+4n-9)}{3(3m^2-m^2n-mn+2n-3)}\\ -\dfrac{\left[\begin{array}{l}9(1+4m-m^2)\\+(mn+2n-3m+3)(2mn-3m+4n-9)\end{array}\right]}{3(6m^2-m^2n-mn-6m+2n)}T^{2(m-1)}\end{array}\right). \quad (35)$$

From equation (6) we obtain

$$R=\left\{\begin{array}{l}\dfrac{\left[\begin{array}{l}12(m-1)(1+m+m^2)\\-4(m+2)(3m^2-m^2n-mn+2n-3)\\-(5m+7)(6m^2-m^2n-mn-6m+2n)\end{array}\right]}{2(m-1)(6m^2-m^2n-mn-6m+2n)}T^{2m-4}\\ -2\left(1+\dfrac{3(1+m+m^2)}{(3m^2-m^2n-mn+2n-3)}\right)T^{-2}\end{array}\right\}. \quad (36)$$

Equation (4) leads to the following expression for the function $f(R)$ of the Ricci scalar

$$f(R)=\frac{K}{2}T^{\frac{(m+2)n}{3}}\left\{\left[\begin{array}{l}\dfrac{6(1+m+m^2)+(mn+2n)(mn+2n-3)}{(6m^2-m^2n-mn-6m+2n)}+\\ \dfrac{(mn+2n-2m-4)(3m^2-m^2n-mn+2n-3)}{(m-1)(6m^2-m^2n-mn-6m+2n)}+\\ \dfrac{(2mn+4n-5m-7)}{2(m-1)}+\\ \dfrac{(1-3\gamma)}{6(1+\gamma)}\left(\dfrac{\left[\begin{array}{l}9(1+4m-m^2)+\\ (mn+2n-3m+3)(2mn-3m+4n-9)\end{array}\right]}{(6m^2-m^2n-mn-6m+2n)}\right)\end{array}\right]T^{2(m-2)}-\left[\begin{array}{l}2+\dfrac{6(1+m+m^2)+(mn+2n)(mn+2n-3)}{(3m^2-m^2n-mn+2n-3)}\\ +\dfrac{(1-3\gamma)}{2(1+\gamma)}\left(1+\dfrac{\left[\begin{array}{l}9(1+4m-m^2)+\\ (mn+2n)(2mn-3m+4n-9)\end{array}\right]}{3(3m^2-m^2n-mn+2n-3)}\right)\end{array}\right]T^{-2}\right\}, \quad (37)$$

which clearly indicates that $f(R)$ depends upon $T$ only.

In the special case when $m=n=2$, $f(R)$ turns out to be

$$f(R)=\frac{K}{3(1+\gamma)}\left(\frac{44}{R}\right)^{\frac{1}{3}}\left[\frac{(265+213\gamma)}{3}+55(41+21\gamma)\frac{1}{R}\right]. \quad (38)$$

This gives $f(R)$ explicitly as a function of $R$ only.

## 6. CONCLUSION:

A Bianchi type-IX cosmological model have been obtained when universe is filled with a perfect fluid in $f(R)$ theory of gravity. The obtained model is singular at $T=0$ and the physical parameters $H$, $\theta$ and $\sigma^2$ are divergent at $T=0$ as well. We observed that the scale factors and volume of the model vanishes at the initial epoch and increases with the passage of time representing an expanding universe. From equations (30) and (32), the mean anisotropy parameter $A_m$ is shown to be constant and $\frac{\sigma^2}{\theta^2}(\neq 0)$ is also constant, hence the model is anisotropic throughout the evolution of the universe except at when $m=1$; *i.e.* the model does not approach isotropy.

It is worth mentioning that, the obtained model is point type singular, expanding, shearing, non-rotating and does not approach isotropy for large $T$. We hope that our model will be useful in the study of structure formation in the early universe and the accelerating expansion of the universe at present.

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Comment [A1]: Cosmological observations such as Cosmic Microwave Background Radiation (CMBR), supernova (SN Ia) and large scale structure are considered as the recent observational data suggesting that the universe is not only expanding but also accelerating.

Comment [A2]: Using the barotropic equation of state $p = \gamma\rho,\ 0 \le \gamma \le 1$ where $\rho$ is the energy density and $p$ is the pressure of the fluid, we conclude that our model is viable for; stiff fluid (), zeldovich fluid (), radiating fluid,

Comment [A3]: In the complete paper F(R) is replaced by F.

Comment [A4]: It is not necessary to give how the equation $a=b^m$ is generated using the assumption that the square of the expansion scalar ($\theta$) is proportional to the shear scalar ($\sigma^2$). The same condition is also used by renowned recent cosmologists like D R K Reddy, Aniruddha Pradhan, K S Adhav, Shriram etc.

Comment [A5, A6, A7, A8]: (i) For Bianchi type-IX space-time the average scale factor is defined as $A = (ab^2)^{\frac{1}{3}}$ where spatial volume $V = ab^2$.

(ii) f(R) is a function of R and F is identical with $F = \frac{d}{dR} f(R)$, automatically F is considered as a function of R where R directly relates with the scale factors a and b as in equation (6). Also The average scale factor A depends upon scale factors which we have defined earlier.

(iii) Such condition has been used by cosmologists Mf. Sharif, K S Adhav in development of cosmological models in f(R) gravity.

Comment [A9, A10]: $\frac{d}{db}(\dot{b}^2) = \frac{d}{dt}(\dot{b}^2)\frac{dt}{db} = 2\ddot{b}$.

Using this equation, equation (21) is converted into linear differential equation of order one where $\dot{b}^2$ is dependent variable and $b$ as an independent variable.

Comment [A11]: In the transformations b is replaced with T and no objection if we keep x, y, z in place of X, Y, Z.